

Sustainability of mild combustion of hydrogen-containing hybrid fuels

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Abstract

Nowadays a process of sensitization on the fundamental problems related to energetic sources and their environmental impact is observed. In this context, the so-called flameless or mild combustion technology offers great advantages in terms of thermal efficiency and pollution emissions with respect to conventional burner-stabilized firing. The achievement of mild conditions requires to heat up the combustion chamber above a threshold temperature and to design the air and fuel jet nozzles so as to obtain dilution factor and jet velocity values larger than their threshold values. However, while it is well known that mild combustion is effective in reducing significantly NO_x emissions and design guidelines are available for standard fuels such as methane, few quantitative information are available for other fuels. This is a limitation to the extension of mild combustion technology to non-conventional fuels, such as industrial by-products and gasification fuels. Consequently, the main aim of this work has been to demonstrate how experimental results obtained in a laboratory-scale burner can be used to identify the main design parameters for burning non-conventional fuels with the flameless technology. In particular, the case of an industrial by-product, the so-called coke oven gas (CH_4/H_2 40/60% by volume), has been considered. It has been found that hydrogen-containing industrial by-products allow sustaining efficient mild combustion conditions. With respect to the well-established flameless combustion of methane, hydrogen-containing fuels require a larger jet velocity and it has been evidenced the possibility to reduce combustion air preheating without flameless extinction, in order to operate with lower average furnace temperatures. Furthermore, it has been demonstrated the ability of hydrogen to lead to completion the hydrocarbon oxidation also in very diluted conditions. These findings, together with the suitability of mild conditions for soot depression, suggest the possibility to perform a hydrogen-assisted flameless combustion of low-calorific dirty fuels.

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1. Introduction

In the last years a global process of sensitization about the fundamental problems related to energetic sources and their environmental impact

has been observed. Since economies based on alternative energetic sources with respect to fossil fuels are not expected to be competitive in the next decades, many researchers have focused their studies on new technologies for a better utilization of fossil fuels in terms of both thermal process efficiency and environmental impact. In this context the relatively new mild technology [1,2], also called flameless [3,4] combustion, offers great

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advantages in terms of thermal efficiency and pollution emissions with respect to conventional burner-stabilized firing.

Mild combustion is usually characterized by both a high preheating of the combustion air fed to the burner and a massive recycle of burnt gases. For this reason, as clearly evidenced both in laboratory-scale burners [5,6] and in several industrial plants [7–10] with conventional fuels, such as methane, flameless processes can easily control and level thermal gradients avoiding the formation of thermal hot spots in the furnace, thus lowering thermal- NO_x emissions [11] without compromising combustion efficiency. The thermal gradients control, and consequently the homogenization of the thermal field in the furnace, is achieved by mild technology through the extension of the combustion in the whole furnace rather than concentrated on a flame front as occurs in common burners. In order to enlarge the combustion region a fast dilution of the reactants is provided by coupling a massive recycle of exhaust gases with high turbulence intensity within the combustion chamber; this is usually achieved by means of separated high-velocity jets of fuel and air. High-velocity jets create a low-pressure region close to the nozzle that entrains a large amount of exhaust gases into the combustion air. The amount of exhaust gases entrained in the reacting jets is usually quantified through a dilution factor, K_V , defined as the ratio between the entrained exhaust gases flow rate (M_e) and the inlet jet flow rate (M_0).

In order to obtain a distributed reaction region (that means a fuel oxidation without a flame front) the Klimov–William criterion must be satisfied [12]. This criterion requires the ratio of the root-mean-square velocity fluctuations (U') to the laminar flame speed (S_L) to be large enough (in particular, $U'/S_L > 1$) and consequently the Damkohler number, which is the ratio between a characteristic mixing time (t_m) and a characteristic combustion time (t_c), to be low enough ($Da = t_m/t_c < 1$) [13]. This means that, as an order of magnitude, turbulence intensity generated by the high-velocity jets must be large enough when compared with the laminar flame speed of the fuel, and that the reaction time must be increased by exhaust gases dilution to be larger than the mixing time between fuel and air. The incoming jets fulfill both these requirements providing high turbulence intensity, which is approximately proportional to the mean flow velocity at the axis ($U' \sim V$), and high exhaust gases entrainment, which roughly decreases proportionally to the jet diameter root square but it does not depend on the jet velocity.

More in detail, the characteristic mixing time can be related to a characteristic jet length (L) and the turbulent eddy diffusivity (ε) as $t_m \sim L^2/\varepsilon$, while the characteristic combustion time can be related to the laminar flame speed and the char-

acteristic premixed flame thickness (δ) as $t_c \sim \delta/S_L$. Since the eddy diffusivity in a jet can be related to the characteristic jet length and axis velocity ($\varepsilon \sim VL$), and the characteristic premixed flame thickness can be related to the kinematic viscosity (ν) as $\delta \sim \nu/S_L$, it follows that for a jet with a given characteristic length and kinematic viscosity, $Da \sim S_L^2/\nu$. Therefore, it is possible to obtain $Da < 1$ both by increasing the jet velocity and by lowering the laminar flame speed, which can be done by increasing the amount of exhaust gases entrained in the jet, thus leading to a vitiated combustion air, with a low oxygen concentration.

Lastly, to be sustained a mild combustion requires a high furnace temperature in order to completely oxidize the fuel also in a low oxygen environment as those created by vitiating the combustion air with the entrained exhaust gases. Below a given average furnace temperature the mild combustion cannot be sustained. In conclusion, a proper design of the air and fuel jet nozzles is required so as to obtain dilution factor and jet velocity values larger than their threshold values. While design guidelines and rules-of-thumb are available for standard fuels, namely methane or natural gas [2,3,5], much less information are available for other fuels. This limits the extension of mild combustion to non-conventional fuels, in particular industrial by-products and gaseous streams that can have burning characteristics quite different from those of the natural gas. Consequently, the main aim of this work has been to demonstrate how main design parameters for non-conventional fuels can be deduced from experimental results obtained in a laboratory-scale burner. In particular, the case of an industrial by-product, the so-called COG or coke oven gas (CH_4/H_2 40/60% by volume), has been considered. The possibility of achieving mild conditions for this fuel has been assessed and the influence of the methane/hydrogen ratio within the fuel has been investigated.

2. Experimental section

The laboratory-scale burner, as well as the recirculation flow pattern that establishes inside the combustion chamber, has been extensively described in detail elsewhere [5,6]. Consequently, only the main features of the equipment are here summarized. The laboratory-scale burner is basically a quartz tube divided in two sections: the combustion chamber and the air preheating section. A single high-velocity nozzle located on the bottom of the combustion chamber constitutes the burner core, into which fuel is fed perpendicularly through a capillary pipe. Inside the nozzle body a partial premixing of fuel and combustion air occurs before the reactants stream enters the combustion chamber, but no combus-

tion takes place due to the small diameter of the pipe and the short residence time. In such a way, a high-velocity jet that entrains a large amount of burnt gases from the combustion chamber through a hydrodynamic entrainment effect is obtained, providing a fast and extended dilution of combustion air. Moreover, an external burnt-gas recycle can be simulated, in addition to the aforementioned internal recycle, by vitiating the combustion air with an inert gas, such as nitrogen. The burner is also provided by a secondary inlet for the combustion air, located on the bottom of the preheating section, that is used during the system start-up [5] to properly preheat the combustion chamber through conventional stabilized flame conditions before switching to “mild” conditions, that are characterized by the absence of a visible flame on the nozzle tip. Both sections of the burner are located in refractory insulated electrical ovens. The lower one provides air preheating up to 1300 °C, simulating the performances of a recuperative industrial heat exchanger, while the upper one is used only to monitor and reduce heat losses from the combustion chamber. For this reason, the upper oven temperature has been set at a value lower than that of the furnace, namely 200 °C below the average value detected continuously by three thermocouples hosted into the furnace at different heights.

This experimental setup allows changing independently the values of the parameters that are relevant for mild conditions achievement, namely: combustion chamber temperature, dilution ratio and jet velocity.

It is a widespread opinion [3,13] that the dilution ratio inside the combustion chamber, K_V , plays a key-role in determining flameless burner working conditions. As a consequence of several calculations performed with a general-purpose code for computational fluid dynamics [5] and accounting also for both internal and external recycle as well as the presence of a secondary air inlet, which flow rate is lower than the entrained one, the K_V value for the laboratory-scale burner can be computed as:

$$K_V = \frac{(Ma_1 + M_f + M_i) \cdot R - Ma_2}{Ma_1 + Ma_2 + M_f} \quad (1)$$

where the flow rates of incoming primary (Ma_1) and secondary (Ma_2) air, inert gas (M_i) and fuel (M_f) have been considered. R is the maximum value of the recycle factor imposed by the jet presence in the chamber; its value is equal to about five for all the conditions investigated.

A usual representation [3,5,6], of the various combustion regimes involves T vs. K_V diagrams as shown, for the sake of example, in Fig. 1. Such a diagram identifies four different regions: traditional combustion (A), transition (B), flameless

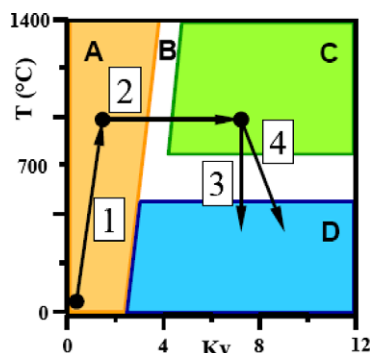


Fig. 1. Common T vs. K_V diagram showing the procedure used for the identification of flameless region boundaries.

(C) and no combustion (D). This diagram, which should be complemented by the information of the jet velocity used, summarizes two relevant design parameters, the minimum average furnace temperature and the minimum dilution ratio required to sustain mild combustion conditions. The laboratory-scale burner can be efficiently used to obtain such diagrams for a given fuel through a simple experimental procedure able to identify the flameless region boundaries. With reference to Fig. 1, such a procedure requires:

- (1) the furnace preheating (step 1); a small amount of air is fed through the nozzle while a secondary air stream is flushed around the nozzle to stabilize a diffusion flame over the tip, allowing for the combustion chamber preheating;
- (2) the transition from traditional combustion to flameless conditions (step 2); this is achieved by gradually decreasing the secondary air flow rate and increasing the primary combustion air flow rate through the nozzle, generating a high-velocity jet that increases the K_V value until, behind a given value of K_V , the system enters the flameless region: this K_V value defines the vertical boundary of the flameless region;
- (3 or 4) the cooling or diluting; the horizontal boundary of the flameless region is identified reducing, at a constant K_V , the preheating furnace temperature so as to cool the combustion chamber (step 3) or replacing a part of the reactants with a nitrogen inert stream simulating a further dilution with exhaust gases, thus increasing the K_V value while reducing the thermal input of the furnace (step 4).

However, it is necessary to define a clear criterion to discriminate between flame, flameless and no combustion region (transition region, depending

on the run, is characterized by an alternate presence of two neighboring conditions). Flameless condition can be easily identified by both the flame disappearing and the reduction of temperature gradients inside the furnace; this usually means a sudden reduction of NO_x emissions but CO_2 yield still higher than 50% (all pollutants concentrations here reported are normalized on a dry basis at 3% O_2 and depurated by the dilution effects due to any inert stream injection). Since the goal of flameless combustion is lowering pollutants emissions, a clean flameless condition has been also defined, imposing to the previously mentioned criterion an additional requirement concerning a maximum pollutants concentration within the exhausts: NO_x below 30 ppm and CO below 50 ppm. The boundaries of a clean flameless region have been defined considering the region were only clean flameless conditions were fulfilled. However, for hydrogen-containing fuels it was observed that the transition from flame to flameless conditions is characterized neither by a sharp transition boundary nor by a clear flame disappearing (particularly for fuels with a high hydrogen content); this leads occasionally to obtain clean flameless conditions outside the region identified as clean flameless. As a consequence, a transition region, where clean flameless conditions are sometimes observed depending on the experimental conditions, has been identified as “mixed zone” in the following.

Thus summarizing, the relevant information that can be obtained from this laboratory-scale burner are the threshold values of both the average furnace temperature and the dilution ratio, as well as a value of the jet velocity allowing to sustain mild conditions.

Apart from the absolute information relative to a given fuel, the experiments can also provide useful relative information. Using a well-characterized fuel (say methane) as a reference, it is possible to point out the influence of the fuel properties on the main design parameters (temperature, K_V and jet velocity) when switching from burning methane to burning a different fuel. These data can be directly used to modify the layout of a real-size burner that is known to work correctly with methane.

3. Results and discussion

As mentioned before, this work is particularly focused on an industrial gaseous by-product, the so-called coke oven gas (COG, with a composition CH_4/H_2 40/60% by volume). The possibility of achieving stable mild combustion for this fuel has been assessed and the influence of the methane/hydrogen ratio in the fuel, with reference to the well-investigated behavior of the pure methane, has been studied by considering also a hybrid

hydrocarbon/hydrogen fuel with a composition CH_4/H_2 70/30% by volume.

Mild combustion of pure methane has been discussed in a previous paper [5]. In the following, results concerning the investigated hybrid hydrocarbon-containing fuels are compared with those of methane; for this reason, the mild operating map for methane is summarized in Fig. 2, where the “mixed zone” is reported together with the clean flameless region. Experimental data concerning methane have been obtained using a relatively low-velocity jet, selecting a nozzle velocity of about 50 m/s. It is possible to notice that the clean flameless region not only is obviously smaller than the mixed zone, but it also shows new limits: an upper temperature threshold and a dilution ratio (K_V) limit. As could be expected, a furnace temperature higher than the upper temperature threshold leads to the formation of a large amount of NO_x , while the K_V upper limit has to be ascribed to an excessive dilution of reactants which creates a too low oxygen environment and, as a consequence, it is observed a high production of CO and an overall worsening of the combustion. For a similar reason, below another temperature limit the combustion efficiency decreases leading to an excessive formation of CO. Inside the clean flameless area mild conditions are stable and easy to be sustained, while in the mixed zone, outside clean mild conditions boundaries, sometimes it is not possible to realize a stable clean mild combustion.

The hydrogen presence within the fuel, as its maximum laminar burning velocity in air is more than six times higher than the corresponding one of methane, did not allow to operate the burner with a relatively low-velocity jet at the nozzle tip; hydrogen confers a high stability to the flame anchored on the nozzle reducing the possibilities to obtain the disappearance of the flame front and a transition from traditional to mild conditions. In this case, as shown for an hybrid 70/30% CH_4/H_2 fuel at a fixed value of $K_V = 5$ in Fig. 3, it is necessary to increase the jet velocity above a critical

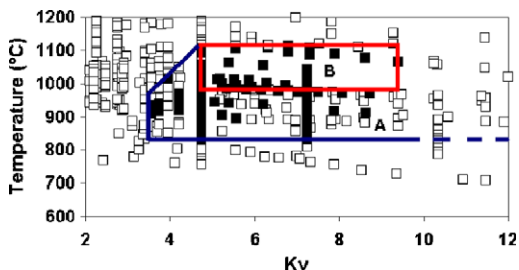


Fig. 2. Flameless operating map for pure methane as a fuel: jet velocity equal to about 50 m/s. Full symbols represent clean flameless conditions; (A) mixed zone and (B) clean flameless region.

value (equal to about 75 m/s for these fuels) to obtain a marked decrease of NO_x emissions and the possibility to attain clean flameless conditions also with hybrid CH_4/H_2 mixtures. This behavior was not observed for methane combustion.

Consequently, as previously discussed, to make the characteristic mixing time from the nozzle up to the region with the highest K_V lower than the characteristic reaction time a much higher jet

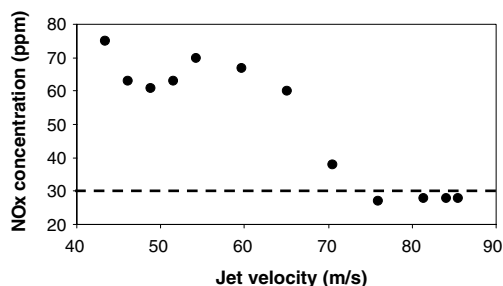


Fig. 3. NO_x concentration as a function of jet velocity at constant $K_V = 5$ for the 70/30% CH_4/H_2 fuel.

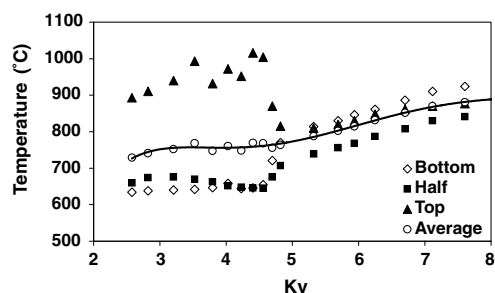
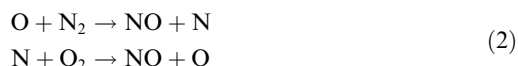


Fig. 4. Thermal profiles in the combustion chamber for the 40/60% CH_4/H_2 fuel.

velocity (at least a 50% larger for H_2 -containing fuels with respect to methane) is required when hydrogen is present.

On the other hand, a hydrogen addition did not significantly affect the combustion chamber thermal homogenization and the CO formation in the mixed zone. As evidenced by a test carried out with a 40/60% CH_4/H_2 fuel (Fig. 4), which reports temperature measures obtained at three different positions inside the combustion chamber as a function of the K_V value, close to the transition, within the mixed zone, the temperature differences in the combustion chamber are definitely reduced, similarly to what happens for methane mild combustion.

All the results of the experiments carried out have been summarized in T vs. K_V diagrams as shown in Fig. 5 for the CH_4/H_2 40/60% by vol., evidencing both mixed zone and clean flameless region boundaries. As previously mentioned, results reported in this diagram have been obtained with a reactants jet velocity larger than 75 m/s. This was an essential requirement for mild combustion to be sustained. Moreover, if we compare the clean mild conditions regions obtained for different hydrogen content within the fuel (Fig. 6), it is possible to point out that the upper temperature threshold, which is close to 1100 °C, is quite unaffected by the presence of the reactive H_2 into the fuel, since in this region NO_x formation is mainly controlled by the Zeldovich mechanism:



whose overall rate strongly depends on temperature and only to a less extent by oxygen

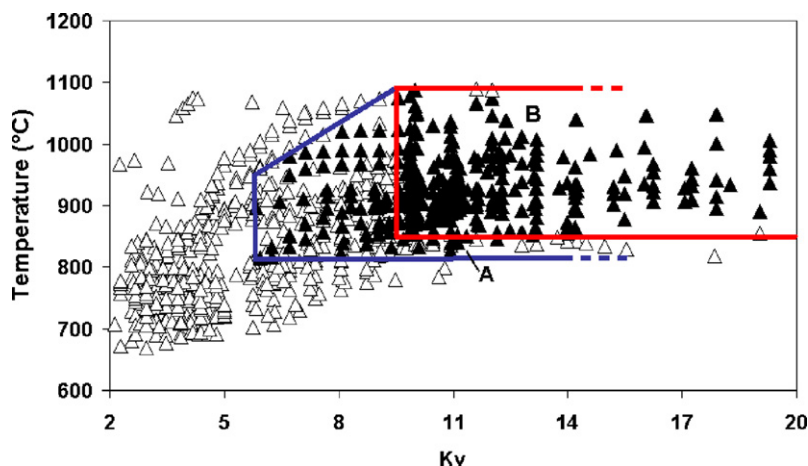


Fig. 5. Flameless operating map for the 40/60% CH_4/H_2 fuel: jet velocity larger than 75 m/s. Full symbols represent clean flameless conditions; (A) mixed zone and (B) clean flameless region.

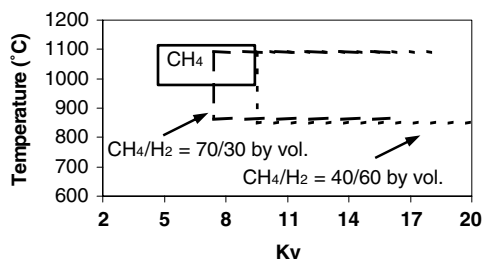
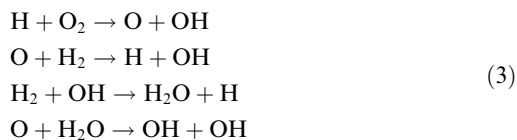


Fig. 6. Clean flameless regions for the three different fuels investigated.

concentration. This mechanism has been considered as the main responsible for the NO_x emissions in the higher temperature region since the transition towards clean flameless combustion evidenced by hydrogen-containing fuels leads to “hot-spots” inside the combustion chamber with temperature values higher than the average furnace temperature. Moreover, the NO_x path through NNH formation from molecular nitrogen and hydrogen radicals could also play a role. Sometimes, it is then possible to find NO_x emissions higher than those expected according to the detected temperatures. In particular, this behavior was evidenced during experimental runs carried out with a strong preheating (namely above 900 °C) of the combustion air, thus leading to a bended boundary in the upper part of the mixed zone. A different behavior has been found for the other boundaries of the clean mild combustion regions. It is clear that hydrogen is able to sustain a clean flameless combustion also in conditions where pure methane combustion produces large amount of CO; this is related to the more reactive characteristics of the hydrogen that is able to create a large pool of radicals that lead the hydrocarbon oxidation to be complete.

In particular, the lower threshold temperature shifts from about 1000 °C for methane to about 870 °C for 70/30% CH_4/H_2 fuel, finally reaching a limit close to 850 °C for 40/60% CH_4/H_2 fuel (Fig. 6). As these modifications did not increase proportionally with the hydrogen content, it can be assumed that the presence of a relatively low amount of hydrogen is able to induce a large decrease in the lower temperature threshold, larger than that obtained by doubling the H_2 concentration within the fuel mixture. Such a behavior can be motivated by the role of hydrogen in the chain branching reactions involved in the oxidation mechanism of any hydrocarbon. The following sequence of radical reactions:



is of great importance in the oxidation mechanism of hydrocarbons since it can provide the necessary chain branching and propagating steps as well as the radical pool for fast reactions [12]. However, the chain branching mechanism is influenced both by the hydrogen concentration and the temperature. At the same dilution ratio, namely a constant oxygen concentration, the sequence of reactions is more dependent on the temperature rather than on the hydrogen amount, since H radicals are regenerated in the close sequence of the first two reactions. Too low temperatures did not allow hydrogen to initiate chain reactions and the hydrogen amount plays a secondary role since no reactions proceed; on the other hand, the chain branching sequence could be initiated if the combustion chamber temperature is sufficiently high, but hydrogen still plays a secondary role due to the sequence of reactions previously reported.

The effect of the hydrogen presence dramatically affects the upper limit of the dilution ratio (K_V), which can be identified only for methane; as this threshold is directly influenced by the kind of fuel, larger is the H_2 amount a more pronounced increase can be evidenced for the upper K_V limit. Considering the clean flameless boundaries reported in Figs. 5 and 6, it is possible to notice that, during experimental tests carried out with hydrogen-containing fuels, an increase of the K_V upper limit up to about 16 and 20 for 70/30% CH_4/H_2 and 40/60% CH_4/H_2 fuels, respectively, did not allow to find a practical upper threshold of the dilution ratio. In this case, at a given temperature, a lower oxygen concentration reduces the importance of the first step of the chain branching mechanism; however, this reduction can be balanced by the increase of the radical chain branching hydrogen molecules, which is involved in the second and third reactions. For this reason, experimental investigations highlighted that higher is the hydrogen amount, less oxygen is required to sustain a complete fuel oxidation, thus allowing a clean mild combustion also for high-diluted environments; it is worth to be noticed that, in such conditions, clean flameless combustion still produced very low CO emissions and a high fuel conversion has been always obtained, as ensured by the on-line monitoring of the exhaust composition. Apart from the very low temperature region, where the system is close to the extinction, no significant escape of unburnt fuel has been found.

A somewhat different consideration should be done for the lower K_V threshold, which seems to increase when hydrogen is added. This behavior has to be ascribed not only to the presence of hydrogen but also to the different jet flow velocity that is required to obtain mild combustion conditions when a high reactive fuel as hydrogen is present. As previously discussed, hybrid CH_4/H_2 mixtures require jet velocity larger than about

75 m/s to realize a marked decrease of NO_x emissions and the possibility to attain clean flameless conditions, while for methane a jet velocity equal to about 50 m/s has been used. The lower dilution ratio threshold seems to be less sensitive to the amount of hydrogen, as evidenced by the comparison between the mixed region lower K_V boundaries obtained at similar jet velocities for the investigated hydrogen-containing fuels. Almost no shift of this K_V limit has been found by doubling the H_2 concentration within the fuel.

Furthermore, it is possible to underline another difference between the investigated hybrid fuels and methane. The transition from traditional flame to mild conditions for methane is mainly characterized by a sudden decrease of the NO_x concentration, which allows to clearly identify the vertical boundary of the mild region, while hybrid CH_4/H_2 mixtures showed a less sharp reduction of NO_x emissions as a function of the dilution ratio. This could be partly ascribed to the high flame stability induced by the hydrogen presence that leads to a more difficult thermal homogenization in the combustion chamber, which is achieved slowly and at a larger K_V value with respect to the case of methane. Such a behavior has been evidenced in Fig. 7 reporting the same data for the 40/60% CH_4/H_2 fuel as in Fig. 5, by modifying the previously defined criterion concerning the maximum NO_x concentration for the clean flameless region identification. In particular, Fig. 7 represents the flameless operating map for the 40/60% CH_4/H_2 fuel obtained considering a NO_x limit equal to about 70 ppm. For comparison purposes, the same figure also reports the clean flameless regions identified by NO_x concentration thresholds of 50 and 30 ppm, respectively. As could be expected, the boundaries for the clean flameless region do not practically change, while the

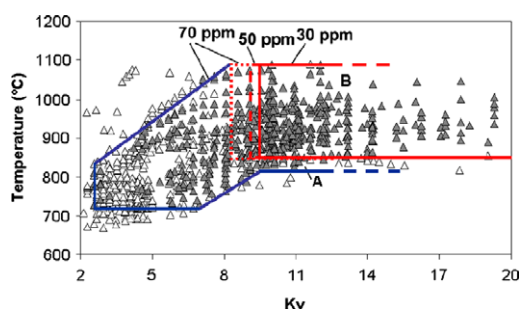


Fig. 7. Flameless operating map for the 40/60% CH_4/H_2 fuel, obtained for a NO_x limit of about 70 ppm. Full symbols represent clean flameless conditions; (A) mixed zone and (B) clean flameless region for NO_x concentrations below (· · ·) 70 ppm. Clean flameless region boundaries for (---) 50 ppm and (—) 30 ppm, respectively, are also reported.

lower vertical limit of the mixed region shifts toward lower K_V values when the NO_x concentration increases, thus extending the region where both clean flameless and non-clean combustion conditions of a hydrogen-added fuel can be theoretically sustained. This explains a somewhat *soft transition* to clean flameless combustion shown by hydrogen-containing fuels.

These results suggest, as main issues, the opportunity to reduce the air preheating when hydrogen is present and to use hydrogen as a chemical doping to allow the sustainability of mild combustion technology also with dirty and low-BTU fuels. The possibility of reducing the combustion air preheating comes directly from the more reactive characteristics of hydrogen which allow to strongly reduce the average furnace temperature, while the possibility of doping low-calorific fuels to burn them efficiently arises from the ability of hydrogen to enhance the full oxidation of hydrocarbons also in very diluted streams.

Since it is well known that soot production markedly depends on the temperature (soot formation is promoted only in an intermediate temperature range) and dilution (longer residence times are required for soot inception and less soot is formed in diluted conditions), mild conditions where both temperature and oxygen decrease represent a suitable environment for soot depression and destruction [2], allowing to foresee its use for a wide range of dirty low-BTU fuels.

4. Conclusions

The achievement of mild conditions requires to heat up the combustion air above a threshold value and to design the air and fuel jet nozzle so as to obtain dilution ratio and jet velocity values larger than their threshold values. Using a laboratory-scale burner it has been shown that the combustion of hydrogen-containing industrial by-products can be efficiently carried out using the flameless technology. Hydrogen-containing fuels require jet velocity larger than those of methane to sustain clean flameless combustion, but allow for using lower average furnace temperatures; moreover, hydrogen is able to enhance, leading to completion, the hydrocarbon oxidation also in very diluted conditions.

These findings, together with the suitability of mild conditions for soot depression, suggest the possibility to perform a hydrogen-assisted flameless combustion of low-calorific dirty fuels. Finally, it has been evidenced that the laboratory-scale burner can be a useful tool for measuring the relevant parameters (furnace temperature, dilution ratio and jet velocity) required to design real-size flameless burners.

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Comments

Bassam Dally, The University of Adelaide, Australia.
How dependent is your findings regarding H_2 on the furnace geometry?

Reply. We used a furnace provided by a single nozzle in which fuel and air are partly premixed before they enter the combustion chamber. This geometry represents the worst case in terms of the possibility to realize mild combustion because when operating the burner with highly-reactive fuels such as hybrid hydrogen-containing mixtures, combustion could start before complete dilution of the reactants with the entrained exhausts is achieved. As a consequence, the relevant macroscopic parameters that should be taken into account to obtain mild conditions are: average furnace temperature, dilution ratio (KV) and jet velocity. Therefore, partly premixed real-size burners that are able to meet the requirements suggested by our findings should allow for sustaining a stable mild combustion of H_2 -hybrid fuels. On the other hand, for burners characterized by

a non-premixed configuration, that means separated high-velocity nozzles for air and fuel, these requirements are probably conservative.

●

Antonio Cavaliere, University Federico II of Naples, Italy. You discuss extensively the NO_x emission. Can you add some information on CO emission, in particular in the transition regions?

Reply. For mild conditions, which means within the clean flameless boundaries that we have identified for the investigated hydrogen-containing hybrid fuels, practically no emissions of CO were detected. Concerning the transition region (the so-called mixed zone), it has usually been found that CO emissions are very low except for the bottom part of the mixed zone where CO emissions larger than 50 ppm can be found due to the progressive worsening of the combustion process at very low temperatures.